Process dependent Sivers function and implications for single spin asymmetry in inclusive hadron production

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We study the single transverse spin asymmetries in the single inclusive particle production within the framework of the generalized parton model (GPM). By carefully analyzing the initial- and final-state interactions, we include the process-dependence of the Sivers functions into the GPM formalism. The modified GPM formalism has a close connection with the collinear twist-3 approach. Within the new formalism, we make predictions for inclusive π^0 and direct photon productions at RHIC energies. We find the predictions are opposite to those in the conventional GPM approach.

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I. INTRODUCTION

Single transverse-spin asymmetries (SSAs) in both high energy lepton-hadron and hadronic scattering processes have attracted considerable attention from both experimental and theoretical communities in over the years [1]. Generally, defined as $A_N \equiv (\sigma(S_\perp) - \sigma(-S_\perp))/(\sigma(S_\perp) + \sigma(-S_\perp))$, the ratio of the difference and the sum of the cross sections when the hadron's spin vector $S_\perp$ is flipped, SSAs have been consistently observed in various experiments at different collision energies [2–4].

Much theoretical progress has been achieved in the recent years. An important realization is the crucial role of the initial- and final-state interactions between the struck parton and the spectators [5], which provide the necessary phases that leads to the non-vanishing SSAs. These interactions can be accounted for by including appropriate color gauge links in the gauge invariant transverse momentum dependent (TMD) parton distribution functions (PDFs) [6–8]. An important example is the quark Sivers function [9], which represents the distribution of unpolarized quarks in a transversely polarized nucleon, through a correlation between the quark's transverse momentum and the nucleon polarization vector. They are believed to be (partially) responsible for the SSAs observed in the experiments.

The details of the initial- and final-state interactions depend on the scattering process, thus the form of the gauge link in the Sivers function is process dependent [10]. As a result, the Sivers function itself is non-universal. For example, it is the difference between the final-state interactions (FSIs) in semi-inclusive deep inelastic scattering (SIDIS) and the initial-state interactions (ISIs) in Drell-Yan (DY) process in *pp* collision that leads to an opposite sign in the Sivers function probed in these two processes [6, 8, 11]. For the hadron production in *pp* collisions, typically the Sivers function has a more complicated relations relative to those probed in SIDIS and DY processes [10]; that is, there are only FSIs (ISIs) in the SIDIS (DY) process, while both ISIs and FSIs exist for single inclusive particle production.

The SSAs for inclusive single particle production in hadronic collisions are among the earliest processes studied in experiments, starting from the fixed-target experiments in 1980s [12]. Recently the experiments at Relativistic Heavy Ion Collider (RHIC) have also measured the SSAs of inclusive hadron production in *pp* collisions over a wide range of energies [4]. Theoretically a QCD collinear factorization formalism at next-to-leading-power (twist-3) has been developed and been used in the phenomenological studies [13–15]. Alternatively, a more phenomenological approach has also been formulated in the context of generalized parton model (GPM) [16–18], with the inclusion of spin and transverse momentum effects. In this approach a TMD factorization is assumed as a reasonable starting point [16]; at the same time, the leading twist TMD distributions (Sivers functions) are assumed to be universal (process-independent); thus the same as those in SIDIS process [19, 20].

In this paper, we formulate the SSAs in inclusive single particle production within the framework of the GPM approach. However, instead of using a process-independent Sivers function, we will carefully examine the initial- and final-state interaction effects, and determine the process-dependent Sivers function. Further we find one can

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carefully move the process-dependence of the Sivers function to the squared hard partonic scattering amplitude under one-gluon exchange approximation, and these modified hard parts are exactly same as those in the twist-3 collinear approach in terms of Mandelstam variables $\hat{s}, \hat{t}, \hat{u}$ (see [14]). This suggests a close connection between this modified GPM formalism and the twist-3 approach. However, it is important to mention that Mandelstam variables $\hat{s}, \hat{t}, \hat{u}$ are themselves a function of partonic intrinsic transverse momentum in the GPM approach. We comment on these issues at the end of Section II. The rest of the paper is organized as follows: In Sec. II, we introduce the GPM approach, and discuss how to formulate the initial- and final-state interaction effects. In Sec. III, we estimate the asymmetry for inclusive pion and direct photon production at RHIC energy, and compare our predictions with those from the conventional GPM approach. We conclude our paper in Sec. IV.

II. INITIAL- AND FINAL-STATE INTERACTIONS IN SINGLE INCLUSIVE PARTICLE PRODUCTION

In this section, we introduce the basic ideas and assumptions of the GPM approach. Then we discuss how to formulate the initial- and final-state interactions for single inclusive particle production. Within the same framework of GPM approach, we thus derive a new formalism for the SSAs of single inclusive particle production, with the process-dependence of the Sivers function taken into account.

A. Generalized Parton Model

Generalized parton model was introduced by Feynman and collaborators [21], as an generalization of the usual collinear pQCD approach. It was adapted and used to describe the SSAs for inclusive particle production recently [16–18], which has had phenomenological success [17]. According to this approach, for the inclusive production of large P_{hT} hadrons (or photons), $A^{\uparrow}(P_A) + B(P_B) \to h(P_h) + X$, the differential cross section can be written as

$$E_h\frac{d\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}f_{a/A^{\uparrow}}(x_a,\vec{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b,k_{bT})\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^U_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \quad (1)$$

where $S = (P_A + P_B)^2$, $f_{a/A^{\uparrow}}(x_a, \vec{k}_{aT})$ is the TMD parton distribution functions with k_{aT} the intrinsic transverse momentum of parton a with respect to the light-cone direction of hadron A, and $D_{h/c}(z_c)$ is the fragmentation function. Since we will only consider the SSAs generated from the parton distribution functions in this paper, we have neglected the k_T-dependence in the fragmentation function. $H^U_{ab\to c}(\hat{s}, \hat{t}, \hat{u})$ is the hard part coefficients with $\hat{s}, \hat{t}, \hat{u}$ the usual partonic Mandelstam variables. Eq. (1) can also be used to describe direct photon production, in which one replaces the fragmentation function $D_{h/c}(z_c)$ by $\delta(z_c - 1)$, and α_s^2 by $\alpha_{em}\alpha_s$.

To study the SSAs, the PDFs $f_{a/A^{\uparrow}}(x_a, \vec{k}_{aT})$ in the transversely polarized hadron A can be expanded as [16–18]

$$f_{a/A^{\uparrow}}(x_a,\vec{k}_{aT}) = f_{a/A}(x_a,k_{aT}) + \frac{1}{2}\Delta^N f_{a/A}(x_a,k_{aT})S_A\cdot(\hat{P}_A\times\hat{k}_{aT}), \quad (2)$$

where S_A is the transverse polarization vector, $\hat{P}_A$ and $\hat{k}_{aT}$ are unit momentum vectors, $f_{a/A}(x_a, k_{aT})$ is the spin-averaged PDFs, and $\Delta^N f_{a/A}(x_a, k_{aT})$ is the Sivers functions. Thus in GPM approach, the spin-averaged differential cross section is given by Eq. (1) with $f_{a/A^{\uparrow}}(x_a, \vec{k}_{aT})$ replaced by $f_{a/A}(x_a, k_{aT})$, while the spin-dependent cross section is given by

$$\begin{aligned} E_h\frac{d\Delta\sigma}{d^3P_h} &= \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}\Delta^N f_{a/A}(x_a,k_{aT})\frac{1}{2}S_A\cdot(\hat{P}_A\times\hat{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b,k_{bT}) \\ &\quad\times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^U_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \end{aligned} \quad (3)$$

and the SSA is given by the ratio,

$$A_N \equiv E_h\frac{d\Delta\sigma}{d^3P_h}\Big/ E_h\frac{d\sigma}{d^3P_h}. \quad (4)$$

As stated in the introduction, there are two assumptions in the GPM approach: one is that the spin-averaged and spin-dependent differential cross sections can be factorized in terms of TMD PDFs as in Eqs. (1) and (3), and the other one is that the Sivers functions is assumed to be universal and equal to those in SIDIS process, $\Delta^N f_{a/A}(x_a, k_{aT}) = \Delta^N f_{a/A}^{\rm SIDIS}(x_a, k_{aT})$. In this paper, we will still work within the framework of the GPM approach, in other words, we will assume the TMD factorization is a reasonable phenomenological starting point. However, at the same time, we will take into account the initial- and final-state interactions. Since both ISIs and FSIs contribute for single inclusive particle production, in principle the Sivers functions in inclusive particle production in hadronic collisions should be different from those probed in SIDIS process. We thus need to carefully analyze these ISIs and FSIs for all the partonic scattering processes relevant to single inclusive particle production to determine the proper Sivers functions to be used in the formalism. In other words, this new formalism will be

$$E_h\frac{d\Delta\sigma}{d^3P_h} = \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}\Delta^N f_{a/A}^{ab\to c}(x_a,k_{aT})\frac{1}{2}S_A\cdot(\hat{P}_A\times\hat{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b,k_{bT}) \times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H^U_{ab\to c}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \quad (5)$$

in which a *process-dependent Sivers function* denoted as $\Delta^N f_{a/A}^{ab\to c}(x_a, k_{aT})$ is used rather than that from SIDIS $\Delta^N f_{a/A}^{\rm SIDIS}(x_a, k_{aT})$ as in the conventional GPM approach.

B. Initial- and final-state interactions

In this subsection, we will discuss how to formulate the initial- and final-state interactions. The crucial point is that the existence of the Sivers function in the polarized nucleon relies on the initial- and final-state interactions between the struck parton and the spectators from the polarized nucleon through the gluon exchange. Thus by analyzing these interactions, one can determine the proper Sivers function $\Delta^N f_{a/A}^{ab\to c}(x_a, k_{aT})$ to be used for the corresponding partonic scattering $ab \to cd$. We start with the classic examples: the final-state interaction in SIDIS, and the initial-state interaction for DY process. To the leading order (one-gluon exchange), they are shown in Fig. 1.

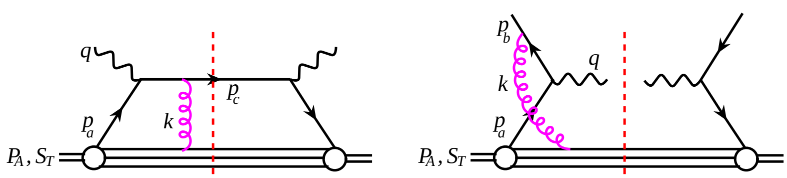

FIG. 1: Final-state interaction in SIDIS (left) and initial-state interaction in DY (right) processes.

For the SIDIS process $e(\ell)+p(P_A,S_T)\to e(\ell')+h+X$ with $Q^2=-q^2=-(\ell'-\ell)^2$, under the eikonal approximation, the final-state interaction (as in Fig. 1(left)) leads to

$$\bar{u}(p_c)(-ig)\gamma^- T^a\frac{i(\not{p}_c-\not{k})}{(p_c-k)^2+i\epsilon}\approx\bar{u}(p_c)\left[\frac{g}{-k^++i\epsilon}T^a\right], \quad (6)$$

where the gamma matrix γ^- appears because of the interaction with a longitudinal polarized gluon ($\sim A^+$), and a is the color index for this gluon. The eikonal part (the term in the bracket) is exactly the first order of the gauge link in the definition of a gauge-invariant TMD PDFs in SIDIS process, see Fig. 2(a). The imaginary part of the eikonal propagator $1/(-k^++i\epsilon)$ provides the necessary phase for the SSAs.

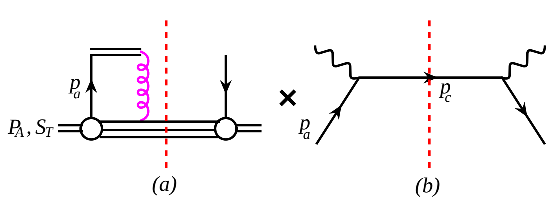

FIG. 2: Sivers function in SIDIS process in the first non-trivial order (one-gluon exchange).

On the other hand, for DY process, the initial-state interaction (as in Fig. 1(right)) leads to

$$\bar{v}(p_b)(-ig)\gamma^- T^a \frac{-i(\not{p}_b + \not{k})}{(p_b + k)^2 + i\epsilon} \approx \bar{v}(p_b)\left[\frac{g}{-k^+ - i\epsilon} T^a\right], \tag{7}$$

which has the same real part and opposite imaginary part compared to SIDIS process. This leads to the fact that the spin-averaged TMD PDFs are the same, while the Sivers function will be opposite in SIDIS and DY processes. This conclusion can be generalized to all order, and has been proven to be true using parity and time-reversal invariant arguments [6, 8].

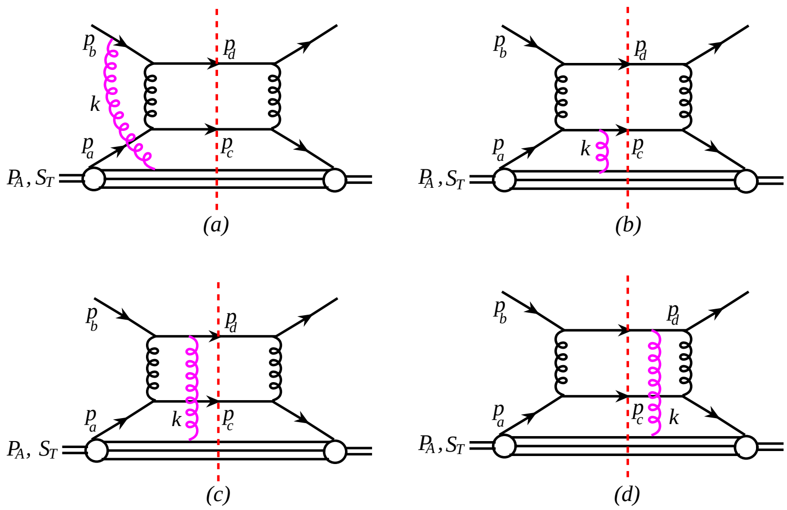

FIG. 3: Initial- and final-state interactions in $qq' \to qq'$: (a) initial-state interaction, (b) final-state interaction, (c) and (d) the final-state interactions for the unobserved particle.

Now let us turn to the case for inclusive single particle production in hadronic collisions, in which $2 \to 2$ partonic scattering is the leading order contribution, where both initial- and final-state interactions contribute. We will start with a simple example: $qq' \to qq'$. Here the initial-quark q is from the polarized nucleon, and the final-quark q fragments to the final-state hadron. The one-gluon exchange approximation for the initial- and final-state interactions are shown in Fig. 3. Under the eikonal approximation, for initial-state interaction Fig. 3(a),

$$\frac{i(\not{p}_b + \not{k})}{(p_b + k)^2 + i\epsilon}(-ig)\gamma^- T^a \bar{u}(p_b) = \left[\frac{-g}{-k^+ - i\epsilon} T^a\right] \bar{u}(p_b), \tag{8}$$

Likewise, for the final-state interaction Fig. 3(b), we have

$$\left[\frac{g}{-k^+ + i\epsilon} T^a\right]. \tag{9}$$

Thus both interactions contribute to the phase $-i\pi\delta(k^+)$, which is the same as in the SIDIS process as in Eq. (6). However, they will have different color flow. To extract the extra color factors for Fig. 3(a) and (b) as compared to the usual $qq' \to qq'$ without gluon attachments, we resort to the method developed in [13, 14, 24]. We obtain the color factors C_I (C_{F_c}) for initial (final)-state interaction

$$C_I = -\frac{1}{2N_c^2}, \qquad C_{F_c} = -\frac{1}{4N_c^2}, \tag{10}$$

while the color factors for unpolarized cross section is given by

$$C_u = \frac{N_c^2 - 1}{4N_c^2}. \tag{11}$$

In other words, the Sivers function in $qq' \to qq'$ should be the one as shown in Fig. 4, which comes from the sum of the ISIs and FSIs with the corresponding color factors C_I and C_{F_c} respectively. Thus by comparing the imaginary part

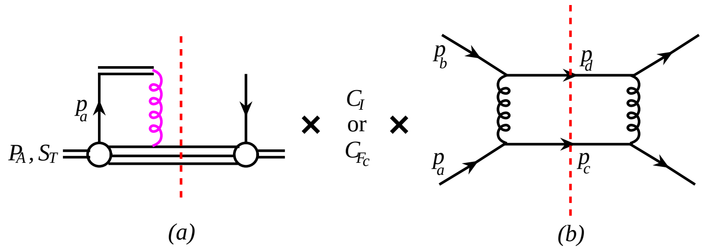

FIG. 4: Sivers function in $qq' \to qq'$ from ISIs and FSIs, with the corresponding color factors C_I and C_{F_c} respectively.

of the eikonal propagators in Eq. (6) for SIDIS and those in Eqs. (8) and (9) for initial- and final-state interaction for $qq' \to qq'$, we immediately find the Sivers function probed in $qq' \to qq'$ process is related to those in SIDIS as follows

$$\Delta^N f_{a/A}^{qq'\to qq'} = \frac{C_I + C_{F_c}}{C_u} \Delta^N f_{a/A}^{\rm SIDIS}. \tag{12}$$

Thus in the GPM model, using the correct Sivers function, one should replace

$$\Delta^N f_{a/A}^{\rm SIDIS} H^U_{qq'\to qq'} \equiv \Delta^N f_{a/A}^{\rm SIDIS} \left[C_u h_{qq'\to qq'}\right], \tag{13}$$

by the following form

$$\Delta^N f_{a/A}^{qq'\to qq'} H^U_{qq'\to qq'} = \frac{C_I + C_{F_c}}{C_u} \Delta^N f_{a/A}^{\rm SIDIS} H^U_{qq'\to qq'} = \Delta^N f_{a/A}^{\rm SIDIS} \left[C_I h_{qq'\to qq'} + C_{F_c} h_{qq'\to qq'}\right], \tag{14}$$

where $h_{qq'\to qq'}$ is the partonic cross section without color factors included. For $qq' \to qq'$, one has

$$h_{qq'\to qq'} = 2\frac{\hat{s}^2 + \hat{u}^2}{\hat{t}^2}. \tag{15}$$

This example tells us that if one uses $\Delta^N f_{a/A}^{\rm SIDIS}$ for the single inclusive particle production, while accounting for the process-dependence of the Sivers function, one should move the process-dependence to the hard parts. In other words, instead of using $H^U_{qq'\to qq'}$ in Eq. (3) for the spin-dependent cross section, one should use

$$H^{\rm Inc}_{qq'\to qq'} \equiv H^{\rm Inc-I}_{qq'\to qq'} + H^{\rm Inc-F}_{qq'\to qq'}, \tag{16}$$

where

$$H^{\rm Inc-I}_{qq'\to qq'} = C_I h_{qq'\to qq'}, \qquad H^{\rm Inc-F}_{qq'\to qq'} = C_{F_c} h_{qq'\to qq'}, \tag{17}$$

are the corresponding hard parts related to initial- and final-state interactions, respectively.

There are many other partonic processes contributing to the single inclusive particle production. Similar to the analysis in $qq' \to qq'$, one needs to analyze each individual Feynman diagram accordingly, carefully moving the extra factors (process-dependence) from the corresponding Sivers function to the hard parts, thus obtaining $H^{\rm Inc-I}_{ab\to cd}$ and $H^{\rm Inc-F}_{ab\to cd}$ for every channel. The modfied formalism will be given in the next subsection.

There are some cautions to our results presented here, especially in Fig. 4. It looks like Figs. 3(a), (b) can be factorized into a convolution of Sivers function and a hard part function as shown in Fig. 4. However, this is not a TMD factorization in the strict sense. Currently TMD factorization theorems have been established for both SIDIS and DY processes [22, 23]. To the order we are studying, this means, the one-gluon exchange diagram for SIDIS in Fig. 1 can be factorized into a convolution of a Sivers function $\Delta^N f_{a/A}^{\rm SIDIS}(x, k_{aT})$ and a hard part function $H(Q)$, as shown in Fig. 2. Here all the soft physics (those depending on k_{aT}) has been absorbed into the Sivers function $\Delta^N f_{a/A}^{\rm SIDIS}(x, k_{aT})$, and the hard part function $H(Q)$ only depends on the hard scale Q, not k_{aT}. On the other hand, for $qq' \to qq'$, we write the corresponding diagram Fig. 3(a) into a similar form: a product of a Sivers function $\Delta^N f_{a/A}^{qq'\to qq'}(x_a, k_{aT})$ and a hard part function $H_{qq'\to qq'}(\hat{s}, \hat{t}, \hat{u})$, as shown in Fig. 4. But as we will comment later, besides the k_{aT} dependence in the Sivers function, one will also need to keep the k_{aT} dependence in the hard part functions $H_{qq'\to qq'}$, without which the SSAs will vanish in both the GPM and this modified GPM formalism. Even though this is not a TMD factorization, one hopes this formalism is a reasonable approximation. There are two reasons to suggest this might be the case. First of all, from phenomenological point of view, this formalism had some success [17]. Secondly, as we will show later this formalism has some connection with the well-established collinear twist-3 approach [14]. As we see here, our identification of the color factors with the hard cross-sections is reminiscent of the results of the twist 3 approach (see in particular [14]). Indeed we will see that upon calculating all partonic processes that contribute from each channel they have the same form in terms of Mandelstam variables $\hat{s}$, $\hat{t}$, $\hat{u}$, as compared to those in the twist-3 collinear factorization approach [14].

To close this subsection, we want to point out the following important fact: the interaction with the unobserved particle (the quark q' for $qq' \to qq'$) vanishes after summing different cut diagrams [13, 14, 25]. To see this clearly, we have for Fig. 3(c),

$$\frac{1}{(p_d-k)^2+i\epsilon}\delta(p_d^2) \to -i\pi\delta((p_d-k)^2)\delta(p_d^2), \tag{18}$$

while the contribution from Fig. 3(d) will be

$$\frac{1}{p_d^2-i\epsilon}\delta((p_d-k)^2) \to +i\pi\delta((p_d-k)^2)\delta(p_d^2). \tag{19}$$

Since the remaining parts of the scattering amplitudes for these two diagrams are exactly the same except for the above pole contributions which are opposite to each other, the contribution from the unobserved particle vanishes. This could also be used to explain why the inclusive DIS process, the SSA vanishes. As shown in Fig. 1 (left), we don't observe the final-state quark for the inclusive DIS process, thus the contribution from the cut to the left and to the right will cancel which results in a vanishing asymmetry.

We want to emphasize that the above analysis holds true only under one-gluon exchange approximation. Going beyond one-gluon exchange, the Sivers functions are typically more complicated, there seems no simple relation (as extra color factors) to those in the SIDIS process [26].

C. Single inclusive hadron production

Now after carefully taking into account both initial- and final-state interactions, the conventional GPM formalism for spin-dependent cross section should be written as

$$\begin{aligned} E_h\frac{d\Delta\sigma}{d^3P_h} &= \frac{\alpha_s^2}{S}\sum_{a,b,c}\int\frac{dx_a}{x_a}d^2k_{aT}\Delta^N f_{a/A}^{\rm SIDIS}(x_a,k_{aT})\frac{1}{2}S_A\cdot(\hat{P}_A\times\hat{k}_{aT})\int\frac{dx_b}{x_b}d^2k_{bT}f_{b/B}(x_b,k_{bT}) \\ &\quad\times\int\frac{dz_c}{z_c^2}D_{h/c}(z_c)H_{ab\to c}^{\rm Inc}(\hat{s},\hat{t},\hat{u})\delta(\hat{s}+\hat{t}+\hat{u}), \end{aligned} \tag{20}$$

where we have a new hard part function $H_{ab\to c}^{\rm Inc}$ instead of $H_{ab\to c}^{U}$ used in the conventional GPM approach. Here the process dependence in the Sivers function has been absorbed into $H_{ab\to c}^{\rm Inc}$, which can be written as

$$H_{ab\to c}^{\rm Inc}(\hat{s},\hat{t},\hat{u}) = H_{ab\to c}^{\rm Inc-I}(\hat{s},\hat{t},\hat{u}) + H_{ab\to c}^{\rm Inc-F}(\hat{s},\hat{t},\hat{u}), \tag{21}$$

where $H_{ab\to c}^{\rm Inc-I}$ and $H_{ab\to c}^{\rm Inc-F}$ are associated with initial- and final-state interactions, respectively. The contributions for the various contributing partonic subprocesses are given by

$$H_{qq'\to qq'}^{\rm Inc-I} = -H_{\bar{q}\bar{q}'\to\bar{q}\bar{q}'}^{\rm Inc-I} = -\frac{1}{N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right] \tag{22}$$

$$H_{qq'\to qq'}^{\rm Inc-F} = -H_{\bar{q}\bar{q}'\to\bar{q}\bar{q}'}^{\rm Inc-F} = -\frac{1}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right] \tag{23}$$

$$H_{q\bar{q}'\to q\bar{q}'}^{\rm Inc-I} = -H_{\bar{q}q'\to\bar{q}q'}^{\rm Inc-I} = -\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right] \tag{24}$$

$$H_{q\bar{q}'\to q\bar{q}'}^{\rm Inc-F} = -H_{\bar{q}q'\to\bar{q}q'}^{\rm Inc-F} = -\frac{1}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right] \tag{25}$$

$$H_{qq'\to q'q}^{\rm Inc-I} = -H_{\bar{q}\bar{q}'\to\bar{q}'\bar{q}}^{\rm Inc-I} = -\frac{1}{N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right] \tag{26}$$

$$H_{qq'\to q'q}^{\rm Inc-F} = -H_{\bar{q}\bar{q}'\to\bar{q}'\bar{q}}^{\rm Inc-F} = \frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right] \tag{27}$$

$$H^{\rm Inc-I}_{q\bar{q}'\to\bar{q}'q} = -H^{\rm Inc-I}_{\bar{q}q'\to q'\bar{q}} = -\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right] \tag{28}$$

$$H^{\rm Inc-F}_{q\bar{q}'\to\bar{q}'q} = = -H^{\rm Inc-F}_{\bar{q}q'\to q'\bar{q}} = \frac{1}{N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right] \tag{29}$$

$$H^{\rm Inc-I}_{qq\to qq} = -H^{\rm Inc-I}_{\bar{q}\bar{q}\to\bar{q}\bar{q}} = -\frac{1}{N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}+\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right]+\frac{N_c^2+1}{N_c^3}\frac{\hat{s}^2}{\hat{t}\hat{u}} \tag{30}$$

$$H^{\rm Inc-F}_{qq\to qq} = -H^{\rm Inc-F}_{\bar{q}\bar{q}\to\bar{q}\bar{q}} = -\frac{1}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right]+\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right]+\frac{1}{N_c^3}\frac{\hat{s}^2}{\hat{t}\hat{u}} \tag{31}$$

$$H^{\rm Inc-I}_{q\bar{q}\to q'\bar{q}'} = -H^{\rm Inc-I}_{\bar{q}q\to\bar{q}'q'} = \frac{1}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right] \tag{32}$$

$$H^{\rm Inc-F}_{q\bar{q}\to q'\bar{q}'} = -H^{\rm Inc-F}_{\bar{q}q\to\bar{q}'q'} = \frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right] \tag{33}$$

$$H^{\rm Inc-I}_{q\bar{q}\to\bar{q}'q'} = -H^{\rm Inc-I}_{\bar{q}q\to q'\bar{q}'} = \frac{1}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right] \tag{34}$$

$$H^{\rm Inc-F}_{q\bar{q}\to\bar{q}'q'} = -H^{\rm Inc-F}_{\bar{q}q\to q'\bar{q}'} = \frac{1}{N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right] \tag{35}$$

$$H^{\rm Inc-I}_{q\bar{q}\to q\bar{q}} = -H^{\rm Inc-I}_{\bar{q}q\to\bar{q}q} = -\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right]+\frac{1}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]-\frac{1}{N_c^3}\frac{\hat{u}^2}{\hat{s}\hat{t}} \tag{36}$$

$$H^{\rm Inc-F}_{q\bar{q}\to q\bar{q}} = -H^{\rm Inc-F}_{\bar{q}q\to\bar{q}q} = -\frac{1}{2N_c^2}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right]+\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]+\frac{1}{N_c^3}\frac{\hat{u}^2}{\hat{s}\hat{t}} \tag{37}$$

$$H^{\rm Inc-I}_{q\bar{q}\to\bar{q}q} = -H^{\rm Inc-I}_{\bar{q}q\to q\bar{q}} = -\frac{N_c^2-2}{2N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\right]+\frac{1}{2N_c^2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]-\frac{1}{N_c^3}\frac{\hat{t}^2}{\hat{s}\hat{u}} \tag{38}$$

$$H^{\rm Inc-F}_{q\bar{q}\to\bar{q}q} = -H^{\rm Inc-F}_{\bar{q}q\to q\bar{q}} = \frac{1}{N_c^2}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}+\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right]-\frac{N_c^2+1}{N_c^3}\frac{\hat{t}^2}{\hat{s}\hat{u}} \tag{39}$$

$$H^{\rm Inc-I}_{qg\to qg} = -H^{\rm Inc-I}_{\bar{q}g\to\bar{q}g} = \frac{1}{2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]+\frac{N_c^2}{2(N_c^2-1)}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\frac{\hat{u}}{\hat{s}}\right] \tag{40}$$

$$H^{\rm Inc-F}_{qg\to qg} = -H^{\rm Inc-F}_{\bar{q}g\to\bar{q}g} = \frac{1}{2N_c^2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{u}}-\frac{\hat{u}}{\hat{s}}\right]-\frac{1}{N_c^2-1}\left[\frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2}\right] \tag{41}$$

$$H^{\rm Inc-I}_{qg\to gq} = -H^{\rm Inc-I}_{\bar{q}g\to g\bar{q}} = \frac{1}{2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{t}}-\frac{\hat{t}}{\hat{s}}\right]+\frac{N_c^2}{2(N_c^2-1)}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\frac{\hat{t}}{\hat{s}}\right] \tag{42}$$

$$H^{\rm Inc-F}_{qg\to gq} = -H^{\rm Inc-F}_{\bar{q}g\to g\bar{q}} = -\frac{1}{2(N_c^2-1)}\left[-\frac{\hat{s}}{\hat{t}}-\frac{\hat{t}}{\hat{s}}\right]-\frac{N_c^2}{2(N_c^2-1)}\left[\frac{\hat{s}^2+\hat{t}^2}{\hat{u}^2}\frac{\hat{s}}{\hat{t}}\right] \tag{43}$$

$$H^{\rm Inc-I}_{q\bar{q}\to gg} = -H^{\rm Inc-I}_{\bar{q}q\to gg} = -\frac{1}{2N_c^3}\left[\frac{\hat{u}}{\hat{t}}+\frac{\hat{t}}{\hat{u}}\right]-\frac{1}{N_c}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\right] \tag{44}$$

$$H^{\rm Inc-F}_{q\bar{q}\to gg} = -H^{\rm Inc-F}_{\bar{q}q\to gg} = -\frac{1}{2N_c}\left[\frac{\hat{u}}{\hat{t}}+\frac{\hat{t}}{\hat{u}}\right]+\frac{N_c}{2}\left[\frac{\hat{t}^2+\hat{u}^2}{\hat{s}^2}\frac{\hat{u}}{\hat{t}}\right] \tag{45}$$

We also calculate the corresponding hard part functions for direct photon production, and they are given by

$$H^{\rm Inc}_{qg\to\gamma q} = -H^{\rm Inc}_{\bar{q}g\to\gamma\bar{q}} = -\frac{N_c}{N_c^2-1}e_q^2\left[-\frac{\hat{t}}{\hat{s}}-\frac{\hat{s}}{\hat{t}}\right] \tag{46}$$

$$H^{\rm Inc}_{q\bar{q}\to\gamma g} = -H^{\rm Inc}_{\bar{q}q\to\gamma g} = \frac{1}{N_c^2}e_q^2\left[\frac{\hat{t}}{\hat{u}}+\frac{\hat{u}}{\hat{t}}\right] \tag{47}$$

Here again we note that all these hard part functions have the same form in terms of Mandelstam variables $\hat{s}$, $\hat{t}$, $\hat{u}$, compared to those in the twist-3 collinear factorization approach [14]. However, the formalisms are different. In the twist-3 collinear factorization approach, all the parton momenta are collinear to the corresponding hadrons, thus $\hat{s}$, $\hat{t}$, $\hat{u}$ does not depend on the parton intrinsic transverse momentum. On the other hand, in the GPM approach, the parton momenta involve intrinsic transverse momentum, thus $\hat{s}$, $\hat{t}$, $\hat{u}$ all depend on the the parton transverse momentum, such as k_{aT} and k_{bT}. In fact, because $\Delta^N f_{a/A}^{\rm SIDIS}(x_a, k_{aT})$ is linear in k_{aT} [20], it is the linear in k_{aT} term in the hard functions $H_{ab\to c}^{\rm Inc}$ that contributes to the asymmetry. Even with this difference, the similarities in terms of $\hat{s}$, $\hat{t}$, $\hat{u}$ suggest that there are close connections between our modified GPM formalism and the twist-3 collinear factorization approach. If one makes an expansion for the hard part functions $H_{ab\to c}^{\rm Inc}$ with respect to k_{aT}, and keeps the first non-trivial term (the linear term in k_{aT}), then using the relation between the Sivers function and the Efremov-Teryaev-Qiu-Sterman function $T_{a,F}(x,x)$ [8],

$$T_{a,F}(x,x) = 2\int d^2k_{aT} k_{aT} \Delta^N f_{a/A}^{\rm SIDIS}(x, k_{aT}) \tag{48}$$

one could derive a formalism that corresponds to a convolution of collinear hard part functions and twist-3 functions $T_{a,F}(x,x)$, which looks very similar to the collinear twist-3 formalism [14]. Whether they are equivalent to each other and how exactly they are related certainly deserves further investigation.

III. NUMERICAL ESTIMATE OF THE SSAS

In this section, we will estimate the SSAs for single inclusive hadron and direct photon production in pp collisions at RHIC energy by using our modified GPM formalism in Eq. (20). We will compare our results with those calculated from the conventional GPM formalism as in Eq. (3).

To calculate the spin-averaged cross section, we use GRV98 LO parton distribution functions [27] along with a Gaussian-type k_T-dependence [19, 20]. The hard part functions for different partonic scattering channels are available in the literature [14, 28, 29]. For the spin-dependent cross section, we use the latest Sivers functions from [20] which are extracted from the recent SIDIS experiments. To consistently use this set of Sivers function, we will use DSS fragmentation function [30]. For the numerical predictions below, we work in a frame in which the polarized hadron moves in the $+z$-direction, choosing $S_\perp$, $P_{h\perp}$ along y- and x-directions, respectively, where all the relevant distribution functions and fragmentation functions evaluated at the scale $P_{h\perp}$ [16].

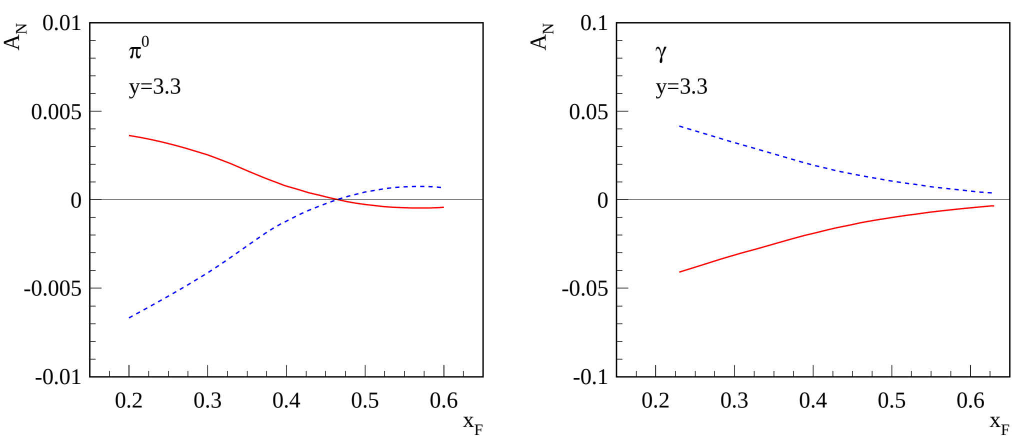

FIG. 5: A_N for inclusive particle production as a function of x_F at RHIC energy $\sqrt{s} = 200$ GeV: $p^\uparrow p \to \pi^0 + X$ (left) and $p^\uparrow p \to \gamma + X$ (right). The dashed curves are for the conventional GPM calculation, and the solid curves are for our modified GPM calculation. We have used the latest Sivers function from [20], and DSS fragmentation function [30].

In Fig. 5, we plot the A_N as a function of x_F for inclusive π^0 (left) and direct photon (right) production at rapidity $y = 3.3$ for RHIC energy $\sqrt{s} = 200$ GeV. The estimates using the conventional GPM formalism in Eq. (3) are shown as dashed lines, while those using our modified GPM formalism in Eq. (20) are shown as solid lines. One immediately see that for both inclusive π^0 and direct photon, A_N change signs compare to the conventional GPM formalism. For π^0, the conventional GPM predicts a negative asymmetry (though very small from this set of Sivers functions), while the modified GPM formalism predicts a positive asymmetry. On the other hand, for direct photon, conventional GPM formalism predicts a positive asymmetry, while modified GPM formalism predicts that the asymmetry is negative, which is consistent with the predictions from twist-3 collinear factorization approach [14]. This can also be easily understood as follows. In the conventional GPM approach, one use H^U in the calculation of the spin-dependent cross section. For direct photon production, the dominant channel comes from $qg \to \gamma q$ with

$$H^U_{qg\to\gamma q} \;=\; \frac{1}{N_c} e_q^2 \left[-\frac{\hat{t}}{\hat{s}} - \frac{\hat{s}}{\hat{t}}\right], \tag{49}$$

while the hard part function in the modified GPM formalism is given by

$$H^{\rm Inc}_{qg\to\gamma q} = -\frac{N_c}{N_c^2-1} e_q^2 \left[-\frac{\hat{t}}{\hat{s}} - \frac{\hat{s}}{\hat{t}}\right]. \tag{50}$$

This introduces an extra color factor $-N_c^2/(N_c^2-1)$, thus opposite to the conventional GPM formalism. This prediction comes from the process-dependence of the Sivers functions, and has the same origin as in the photon+jet calculation [31].

On the other hand, for the inclusive π^0 production, the dominant channel comes from $qg \to qg$, particularly in the forward direction, one has

$$H^{\rm Inc}_{qg\to qg} = H^{\rm Inc-I}_{qg\to qg} + H^{\rm Inc-F}_{qg\to qg} \to -\frac{N_c^2}{2(N_c^2-1)}\frac{2\hat{s}^2}{\hat{t}^2} - \frac{1}{N_c^2-1}\frac{2\hat{s}^2}{\hat{t}^2} = -\frac{N_c^2+2}{N_c^2-1}\frac{\hat{s}^2}{\hat{t}^2}, \tag{51}$$

where we have used that in the forward direction, $\hat{t}$ is small, while $\hat{u} \sim -\hat{s}$, whereas

$$H^U_{qg\to qg} = \frac{N_c^2-1}{2N_c^2}\left[-\frac{\hat{s}}{\hat{u}} - \frac{\hat{u}}{\hat{s}}\right] + \frac{\hat{s}^2+\hat{u}^2}{\hat{t}^2} \to \frac{2\hat{s}^2}{\hat{t}^2}. \tag{52}$$

We thus also see the sign is reversed in our modified GPM formalism compared with the conventional GPM approach.

We observe that the x_F-dependence in both modified and conventional GPM formalisms are different from those observed in the RHIC experiments where larger asymmetries have been observed in the forward direction (large x_F) [4]. Of course, in order to have a comparison with the experimental data for inclusive hadron production at RHIC experiments, one must include both Sivers (as studied in this paper) and Collins effects [32]. The latter describes a transversely polarized quark jet fragmenting into an unpolarized hadron, whose transverse momentum relative to the jet axis correlates with the transverse polarization vector of the fragmenting quark. This correlation in the fragmentation functions could also generate the transverse spin asymmetry, which is not studied in our paper. Currently attempts at global fitting with both SIDIS and pp experimental data are ongoing [18]. We encourage the use of the modified GPM formalism in such a global analysis, to study the effect of the associated ISIs and FSIs (process-dependence of the Sivers functions). We also point out that there is only Sivers contribution in direct photon production. Since the modified and conventional GPM predict opposite asymmetries, direct photon production presents a favorable opportunity to test the process dependence of the Sivers function, or the effect of the associated ISIs.

IV. SUMMARY

In this paper, we have studied the single transverse spin asymmetries in the single inclusive particle production in hadronic collisions. We point out the Sivers functions in such processes are generally different from those probed in the SIDIS process because of different initial- and final-state interactions. By carefully taking into account the process-dependence in the Sivers functions (under one-gluon exchange approximation), we derive a new formalism within the framework of GPM approach. We find this formalism has close connections with the collinear twist-3 approach. With our modified GPM formalism, we make predictions for the inclusive π^0 and direct photon production in pp collisions at RHIC energies. We find that the asymmetries predicted from the modified GPM formalism are opposite to those in the conventional GPM approach. This sign difference comes from the color gauge interaction, which has the same origin as the sign change for Sivers functions between SIDIS and DY processes. Our predictions about the sign are consistent with those from the twist-3 collinear factorization approach. We encourage a global analysis of both SIDIS and pp experimental data using this modified GPM formalism.

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